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PRELIMINARY COMPUTATIONS ON THE "TEITEL" DESIGN BREEDER REACTOR

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1. Introduction.

The following are preliminary calculations based upon a bare, homogeneous, poison-free pile of the Teitel design. No assumptions have been made as to engineering feasibility - in fact, no such specifications were known at the time of calculation - so that the results are in the main exploratory. A more practical set of computations is forthcoming and awaits only the engineers' decisions on certain details.

2. Basis of Calculation.

The pile utilizes a graphite core containing U^{233} suspended in an intermetallic compound of lead and tin. This combination is assumed to contain uranium, lead and tin, in atom per cents of 3.75, 83.25, and 13, respectively. Through the core and heat exchanger is circulated a coolant solution of Th^{232} and liquid Bi, in 4 and 96 atom per cents respectively, part of which is diverted into a blanket area, where the thorium is utilized for breeding. Of course breeding will take place in the reactor core as well.

We designate by numbers from 1 to 6 the elements involved, which we list below along with their pertinent properties.

1. $\underline{U^{233}}$

$\eta = 2.37$

$\sigma_a = 564.6$ barns

$\sigma_s = 8.2$ barns

$\rho = 18.7$

$A = 233$

2. Th

$\sigma_a = 7.0$

$\sigma_s = 13.0$

$\rho = 11.5$

$A = 232$

3. Bi

$\sigma_a = .032$ barns

$\sigma_s = 9$

$\rho_{liq} = 10.00$

$A = 209$

4. C (graphite)

$\sigma_a = .0044$ barns

$\sigma_s = 4.8$ barns

$\sigma_t = 4.44$

$\rho = 1.60$

$A = 12$

$\tau = 364$ cm

$L = 54.4$ cm

$L^2 = 2959.36\ \text{cm}^2$

5. Pb

$\sigma_a = .17$ barns

$\sigma_s = 11$ barns

$\rho_{liq} = 10.6$

$A = 207$

6. Sn

$\sigma_a = .65$ barns

$\sigma_s = 4$ barns

$\rho_{liq} = 6.99$

$A = 119$

The breeding gain of the reactor is given by

$$(1)\quad G = \gamma_{21}\,\sigma_{a21} + \left\{(\eta-1) - \sum_{j=2}^{6} \gamma_{j1}\,\sigma_{aj1}\right\}\beta \ ,$$

where

$$(2)\quad \beta = \frac{1}{1 + \gamma_{32}\,\sigma_{a32} + \gamma'_{42}\,\sigma_{a42}} \quad .$$

(See Fig. 1). Here the subscripted quantities represent ratios:

$\gamma_{ij} = N_i/N_j$

$\sigma_{aij} = \sigma_{ai}/\sigma_{aj}$,

γ'_{42} refers to the graphite-thorium atom ratio in the blanket. Obviously the bismuth-thorium atom ratio is the same for blanket and core. We have assumed that no fissionable material is present in the blanket, i.e., that processing is instantaneous. The critical mass of uranium in the reactor core can be obtained from the following formulae, which need no explanation.

$$(3) \quad k_\infty = \eta \frac{1}{1 + \sum_{j=2}^{6} \gamma_{j1} \sigma_{aj1}}$$

$$\tau = \frac{(1 + \sum_{i \neq 4} \gamma_{i4} \rho_{4i} A_{i4})^2 \tau_{graphite}}{(1 + \sum_{i \neq 4} \gamma_{i4} \sigma_{ti4})}$$

$$L^2 = \frac{(1 + \sum_{i \neq 4} \gamma_{i4} \rho_{4i} A_{i4})^2 L^2_{graphite}}{\left\{1 + \sum_{i \neq 4} \gamma_{i4} \sigma_{ai4}\right\} \left\{1 + \sum_{i \neq 4} \gamma_{i4} \sigma_{ti4}\right\}}$$

$$k_\infty \frac{e^{\Delta \tau}}{1 - L^2 \Delta} = 1$$

$$V_c = \frac{148.2}{(-\Delta)^{3/2}}$$

$$M_c = \frac{\rho_1 V_c}{1 + \sum_{j \neq 1} \gamma_{j1} \rho_{1j} A_{j1})}$$

Here $A_{ij} = \frac{A_i}{A_j}$, $\rho_{ij} = \frac{\rho_i}{\rho_j}$ (density ratio), $\sigma_{t_{ij}}$ is a transport cross section ratio, and V_c is the critical volume for a minimum right cylinder.

3. <u>Graphite Concentration in the Blanket.</u>

For maximum efficiency the breeder blanket must be effectively infinite. Consider an infinite slab blanket. Then the two group neutron diffusion equations in the blanket may be written:

(4) $D_f\nabla^2\phi_f - \Sigma_f\phi_f = 0$

$D_{th}\nabla^2\phi_{th} - \Sigma_s\phi_{th} + \Sigma_f\phi_f = 0$, or

(4a) $\nabla^2\phi_f - K_f^2\phi_f = 0$

$\nabla^2\phi_{th} - K_{th}^2\phi_{th} + K'^2\phi_f = 0$,

since the blanket contains no fast neutron sources. Here

$K'^2 = \Sigma_f/D_{th}$

(5) $K_f^2 = \Sigma_f/D_f = 1/\tau$

$K_{th}^2 = \Sigma_{th}/D_{th} = 1/L^2$,

τ being the age to thermal energy and L the thermal diffusion length. The solution for the thermal flux has the form:

(6) $\phi_{th} = Ae^{-x/L} + Be^{-x/\sqrt{\tau}}$,

where the constants A and B can be determined from equations (4a) and the flux at the boundary (x = 0). Evidently the blanket will be effectively infinite* providing that

$t > n\cdot\max(\sqrt{\tau}, L)$,

where t is the blanket thickness and n is an arbitrary number but at least equal to three. Fig. 2 shows a plot of $\sqrt{\tau}$ and L versus γ'_{43}, the graphite to bismuth ratio in the blanket, showing that for all cases of practical interest, namely $\gamma'_{43} \leq 10$, $\sqrt{\tau}$ is the determining factor. Also since the curves for L and $\sqrt{\tau}$ cross at about this point, larger graphite concentrations than this would only require thicker blankets.

4. Results.

The computations were made by first assuming a value of g and then determining the pile specifications for a variety of values of γ'_{43}, hence t. The

*That is, essentially all neutrons will have been thermalized and absorbed within the blanket width.

only optimization attempted is the variation of γ_{43} the internal graphite-bismuth ratio, for minimum critical mass of U^{233}. Naturally, thinner blanketed (high γ'_{43}) piles are to be associated with lower breeding gains; thicker blanketed piles, having less parasitic capture in carbon, with higher gains. It can be shown that for

$$\beta = g/1.36 = \beta_o$$

all breeding would be done externally, hence no coolant could be circulated in the core. Thus, it is meaningful to speak of a given g only if $\beta < \beta_o$. The maximum possible power removable is computed on a basis of a flow rate of 10 ft/sec and a temperature rise of 300°C. A temperature correction factor of $\sqrt{T/T_o} = \sqrt{2}$ has been applied in computing L^2.

<u>Table 1.</u>

$g = 1.1,\ \beta = .790,\ \gamma'_{43} = 10,\ t \approx 66$ cm

γ_{43}	γ_{21}	γ_{31}	γ_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (MW)
7.75	88.6	---	---	1.1	0	∞	∞	∞	---	---
7.5	77.8	1945	481	.971	.129	326	602	305	536	10217
7.0	63.1	1576	1088	.786	.313	200	370	91.7	130.4	4045
6.0	45.7	1143	1878	.569	.531	144	265	52.2	53.7	2324
5.5	40.2	1005	2949	.500	.600	135	248	51.3	46.4	2144
5.0	35.9	896	4482	.446	.654	127	235	51.6	41.6	2037
4.0	29.5	737	5526	.367	.733	122	225	62.9	41.7	2129
3.0	25.0	626	6857	.311	.789	122	225	86.3	48.6	2481
2.0	21.8	544	11036	.271	.829	132	244	152	74.3	3496
1.0	19.2	481	14593	.239	.861	163	302	407	175.9	6680

Table 2.

$g = 1.15,\ \beta = .790,\ \gamma'_{43} = 10,\ t \approx 66$ cm

γ_{43}	γ_{21}	γ_{31}	γ_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	$M_{Bi}x10^{-3}$(kg)	Power (MW)
4.31	92.7	---	---	1.15	0	∞	∞	∞	---	---
4.0	87.3	2183	8730	1.08	.07	475.8	879	1287	2519	32,901
3.5	80.17	2004	7015	.994	.156	314.6	581	437	784	15,497
3.0	74.11	1852	5558	.919	.231	261.1	482	291	484	11,518
2.5	68.91	1723	4307	.854	.296	236.5	432	250	394	10,348
2.0	64.39	1610	3220	.798	.352	227.4	420	267	386	10,537
1.0	56.92	1423	1423	.706	.444	248.1	458	492	628	15,725

Table 3.

$g = 1.15,\ \beta = .8168,\ \gamma'_{43} = 7,\ t \approx 72$ cm

γ_{43}	γ_{21}	γ_{31}	γ_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	$M_{Bi}x10^{-3}$(kg)	Power (MW)
4.31	92.7	---	---	1.15	0	∞	∞	∞	---	---
4.0	82.2	2054	8215	1.02	.13	344	636	516	951	7167
3.5	70.4	1759	6159	.874	.276	233	430	201	317	8469
3.0	61.6	1539	4618	.764	.386	199	368	156	216	6725
2.5	54.7	1368	3420	.679	.471	184	340	151	186	6265
2.0	49.2	1231	2462	.611	.539	179	332	171	189	6540
1.0	41.0	1026	1026	.509	.641	204	377	377	346	10557

Table 4.

$g = 1.15$, $\beta = .8383$, $Y'_{43} = 5$, $t \approx 78$ cm

Y_{43}	Y_{21}	Y_{31}	Y_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (MW)
4.31	92.7	---	---	1.15	0	∞	∞	∞	---	---
4.0	61.0	1526	6102	.757	.393	182	336	102	140	4789
3.0	30.4	760	2101	.377	.773	128	237	86.7	59.1	2869
2.5	24.3	608	1520	.302	.848	123	229	102	55.8	2802
2.0	20.3	506	1013	.251	.899	127	235	145	66.0	3229
1.0	15.2	380	3796	.188	.962	157	289	447	152	6048

Table 5.

$g = 1.20$, $\beta = .79$, $Y'_{43} = 10$, $t \approx 66$

Y_{43}	Y_{21}	Y_{31}	Y_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (MW)
1.17	96.7	---	---	1.2	0	∞	∞	∞	---	---
1.1	95.7	2392	2631	1.19	.01	1550	2864	69,810	149,790	6.0×10^5
.75	91.9	2296	1723	1.14	.06	812	1501	11,460	23,620	1.8×10^5
.5	89.4	2235	1117	1.10	.09	771	1425	10,820	21,690	1.75×10^5
.25	87.0	2175	544	1.08	.12	908	1678	19,590	38,220	2.6×10^5

Table 6.

$g = 1.2$, $\beta = .8168$, $\gamma_{43}^{\prime} = 7$, $t \approx 72$ cm

γ_{43}	γ_{21}	γ_{31}	γ_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (MW)
1.17	96.7	---	---	1.2	0	∞	∞	∞	---	---
1.1	94.9	2375	2612	1.18	.02	1023	1890	20,203	43,040	2.61×10^5
.75	89.7	2242	1681	1.11	.09	680	1257	6894	13,863	1.27×10^5
.50	86.2	2155	1078	1.07	.13	653	1206	6791	13,130	1.25×10^5
.25	83.0	2076	519	1.03	.17	775	1432	12,736	23,700	1.90×10^5

Table 7.

$g = 1.2$, $\beta = .8495$, $\gamma_{43}^{\prime} = 4$, $t \approx 81$ cm

γ_{43}	γ_{21}	γ_{31}	γ_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (MW)
1.17	96.7	---	---	1.2	0	∞	∞	∞	---	---
1.0	90.1	2253	2253	1.12	.08	624	1153	4963	10,029	99,800
.75	83.2	2079	1560	1.03	.17	480	887	2610	4868	63,018
.60	79.5	1987	1192	.99	.21	463	856	2561	4565	61,210
.50	77.2	1930	965	.96	.24	470	868	2834	4907	64,230
.25	72.0	1802	450	.89	.31	573	1058	5916	9560	103,690

Table 8.

$g = 1.2$, $\beta = 879$, $Y'_{43} = 1.5$, $t \approx 108$ cm

Y_{43}	Y_{21}	Y_{31}	Y_{41}	g_{int}	g_{ext}	R_o(cm)	H_o(cm)	M_c(kg)	M_{Bi}x10^{-3}(kg)	Power (Mw)
1.17	96.7	---	---	1.2	0	∞	∞	∞	---	---
1.1	71.0	1777	1954	.88	.32	306	566	724	1155	23,400
1.0	56.6	1414	1414	.70	.50	248	458	492	625	15,650
.75	37.4	936	702	.46	.74	218	403	539	453	12,890
.60	31.1	779	467	.39	.81	225	416	711	497	13,700
.50	28.0	700	350	.35	.85	237	439	988	620	16,200
.25	22.3	559	140	.27	.93	308	570	2901	1454	29,300

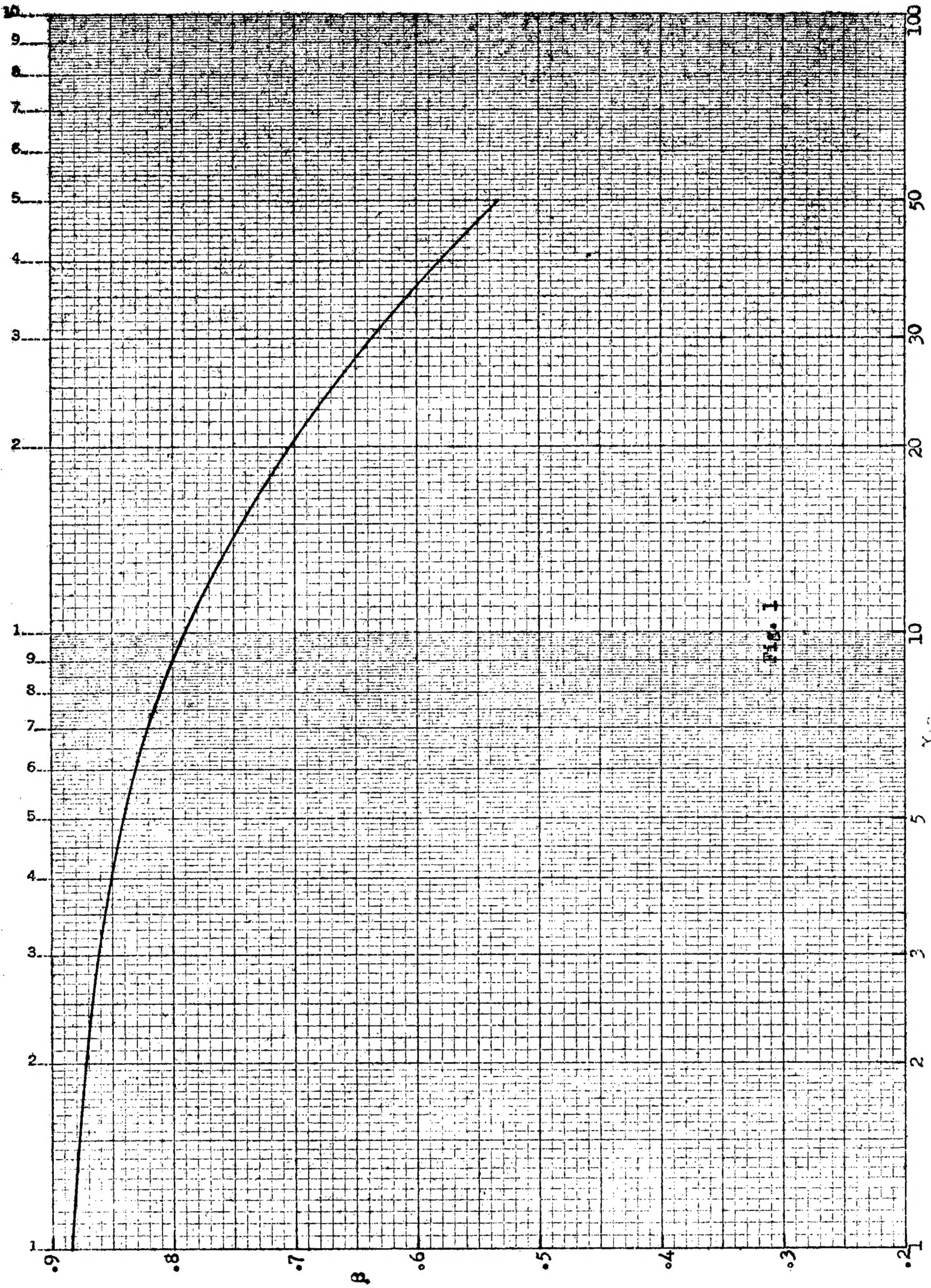

Fig. 1

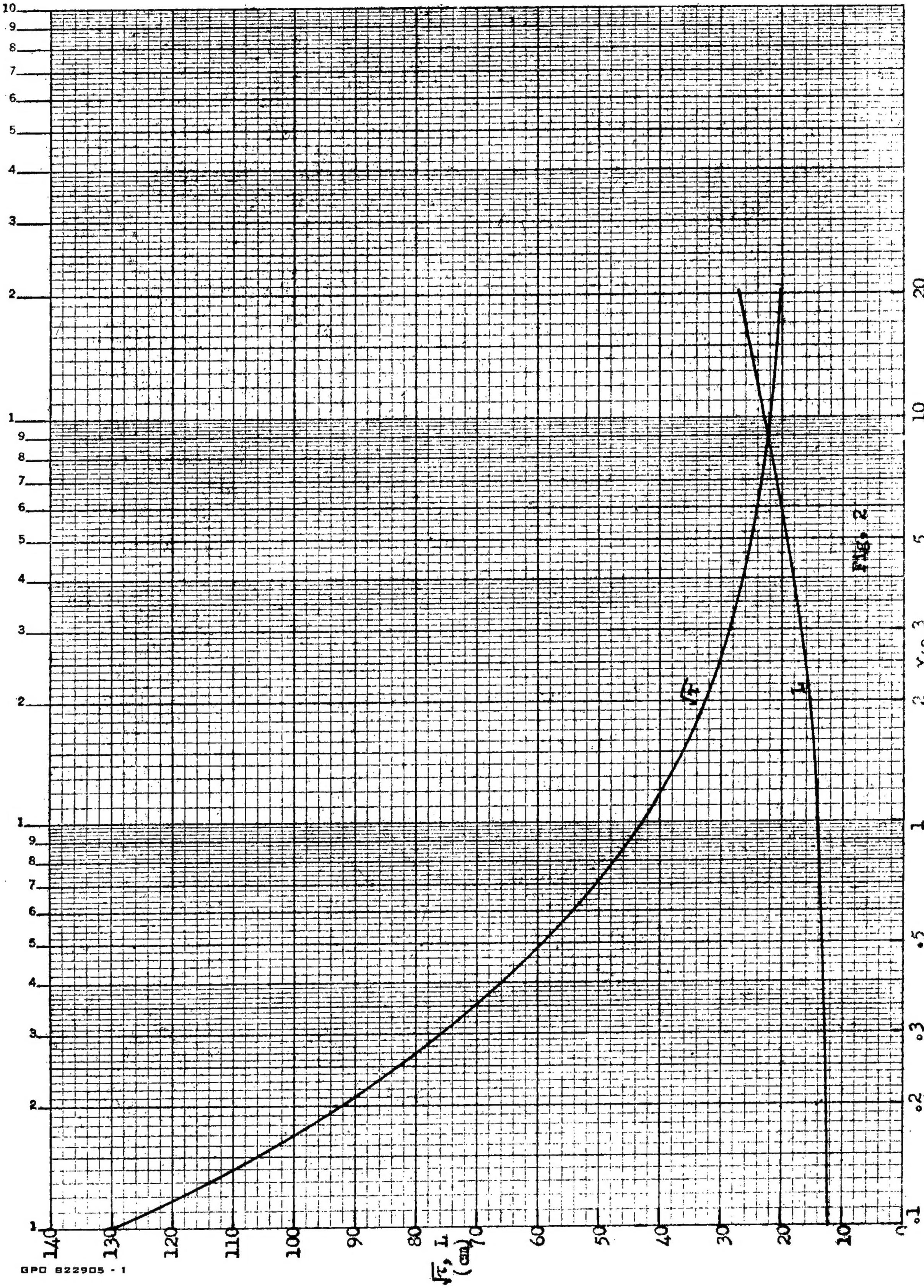

Fig. 2

GPO 822905 - 1